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NITRATE LOADING AND IMPACTS ON CENTRAL WISCONSIN GROUNDWATER BASINS

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INTRODUCTION

Nitrate is Wisconsin's most common groundwater pollutant. Agriculture is the largest nitrate source, accounting for about 90% of that which leaches to groundwater (Shaw, 1994). Only recently have the university and state agencies put together sufficient pieces of the nitrate puzzle to realize the extent of nitrate pollution (e.g., Central Wisconsin Groundwater Center, 1994; LeMasters and Baldock, 1997) and that it is increasing (e.g., Albertson and Shaw, 1998; Mason et al. 1990). A steep increase in groundwater nitrate began in the 1960s, coinciding with a large increase in chemical fertilizer-N use (Hallberg, 1989). Fertilizer-N use more-or-less leveled only about 15-20 years ago, but groundwater nitrate continues to increase. The continuing increase is due to the length of groundwater residence times (averaging decades to centuries, depending on the basin) relative to the short duration (~40 years) of increased fertilizer-N use. Groundwater nitrate concentrations and export from basins will continue to increase until aquifers equilibrate with modern nitrate loading rates.

Concerns about nitrate pollution are both human-health and environmentally driven. The drinking water standard is based on methemoglobenemia risk to infants. Other potential health concerns have been suggested, including spontaneous abortion , non-Hodgkin's lymphoma, and others. Environmental concerns result when nitrate-polluted groundwater discharges to surface water. Nitrate concentrations at about the drinking water standard cause mortality to the egg and fry of some fish (Kincheloe et al., 1979) and to the egg and tadpoles of some amphibians (Hecnar et al., 1995). Nitrate pollution discharging from terrestrial systems threatens major N-limited aquatic ecosystems, such as the Chesapeake Bay and Gulf of Mexico at the mouth of the Mississippi River.

Especially since nitrate is widespread, increasing, and largely uncontrolled, it seems critical to determine what concentrations of nitrate will be attained in Wisconsin's groundwater basins given current loading rates. Perhaps the best way to make this determination is to examine the nitrate impacts of particular agricultural systems in particular physical settings. In this vein, this paper focuses on the nitrate impacts from production systems in Wisconsin central sand plain groundwater basins.

THE WISCONSIN CENTRAL SAND PLAIN

The Wisconsin central sand plain (WCSP, Figure 1) is a 6400 km^2 area characterized by level topography and a mantle of sandy deposits frequently over 30 m thick. Agriculture there consists of irrigated vegetable rotations, cash grain, hay, and dairy. Groundwater is substantially impacted by nitrate and pesticides. In the Agricultural Statistics District that includes the WCSP,

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22% of domestic wells exceed the nitrate standard. However, where irrigated vegetable agriculture is dominant, over 70% of wells may exceed the standard. The salient features of the agricultural system and physical setting that contribute to groundwater impacts include the following:

Rotation:	Vegetables (potato, snap bean, sweet corn, soy bean, pea), field corn, soy bean, hay, dairy.
Inputs:	Irrigation water; large amounts of fertilizer and pesticide.
Climate:	Warm, humid summers; cool snowy winters.
Soils:	Coarse, drouthy.
Aquifer:	Shallow, fast-responding.

NITRATE POLLUTION AT THE FIELD SCALE

Perhaps the most detailed studies of nitrate concentrations and loadings under WCSP vegetable fields were made by Stites and Kraft (1997; 2000a,b), who monitored the upper 10 feet of groundwater under four fields. Crops grown during the study were sweet corn and potato.

Nitrate-N concentrations under the vegetable fields averaged about 20 mg/L, even when grower inputs of N fertilizer were made according to University recommendations. The 20 mg/L average is probably a best case scenario, because no agricultural land uses were present upgradient of the study fields. Similar studies performed by Curwen et al. (1991) reported average nitrate-N concentrations of 40-50 mg/L, even using University recommended N applications.

From a groundwater basin perspective, knowledge of nitrate-N loading (pounds per acre per year) is more important than nitrate-N concentration. Loading rates allow prediction of basin-scale groundwater quality, and perhaps the design of better agricultural practices to meet groundwater goals. Nitrate-N loadings measured by Stites and Kraft (1997) averaged 138 lbs/acre-yr over a four year period (Table 1). This amounted to 75% of fertilizer-N and 62% of the total N inputs. Loading rates were large even when fertilizer-N applications approximated university recommendations. Stites and Kraft also found that loading rates calculated from an N-budget approach matched well with measured rates. The agreement between measured and budget-derived loading suggests that the budget method can be used for estimating nitrate loading under Wisconsin central sand plain vegetable production systems.

SCALING UP FROM FIELDS TO BASINS - MONITORING

Few monitoring studies have been conducted at the basin scale measuring the impacts of WCSP agricultural systems on downgradient water quality. Perhaps the most detailed (Kraft and Stites, 1999) involved a 10 mi^2 WCSP groundwater basin that contained about 1500 acres (22%) of the irrigated vegetable agriculture land use. Other land uses consisted of woods, grassland, and unsewered residential development. Kraft and Stites found that plumes from vegetable fields underlay about 54% of the basin. The plumes were 10 to 35 feet thick

Table 1. Fertilizer applications and nitrate loading under a WCSP irrigated vegetable field, 1992-1995 (Stites and Kraft, 1997).

		1992	1993	1994	1995	Avg.
Crop	Type	S. corn	Potato	S. Corn	S. Corn	
	Yield	11 ton/a	410 cwt/a	9.5 ton/a	9 ton/a	
Fertilizer-N (lbs/acre)						
	Applied	223	292	185	157	214
	University recommended	160	230	160	160	257
	Excess beyond recommended	63	62	15	-3	43
Nitrate-N loading[1]						
	lbs/acre	159	121	153	118	138
	% of fertilizer-N	71	61	83	75	74
	% of total N input	60	71	68	60	62

[1] Loading amounts shown are from monitoring. N budget estimates are similar.

downgradient of individual fields, and sometimes occupied the entire thickness of the aquifer (50 feet or more) when plumes from two or more fields overlapped (Figure 2). Nitrate-N concentrations in agricultural plumes averaged about 14 mg/L, while groundwater outside of plumes averaged only 0.5 mg/L. The agricultural impacts in this basin are likely less severe than in many irrigated parts of the WCSP, because the density of the agricultural land use was lower than what is typical.

SCALING UP FROM FIELDS TO BASINS - A MASS-BALANCE APPROACH

Though monitoring studies are useful and necessary, they have limited utility: monitoring studies are limited to the specific area in which they are employed, offer only a snapshot of conditions while the monitoring was being performed, and taken alone, do not predict future conditions. Some simple mass-balance modeling, however, allows predictions of what nitrate concentrations might ultimately be achieved under present and potential land uses and land management.

A mass balance modeling approach was used by Mechenich and Kraft (1997) for recharge areas of the Village of Plover and Village of Whiting municipal wells. They predicted what nitrate concentrations will evolve given present land uses and land management, attributed nitrate sources to specific land uses, described the degree of improvement that might be possible through the use of best management practices, and examined what other changes might be needed to achieve nitrate reductions. Their mass balance approach predicted steady-state, basin-averaged nitrate concentration in ground-water. Steady-state will occur when nitrate levels in the groundwater are in equilibrium with nitrate loading from the surface.

Presently, both the Whiting and Plover municipal wells exceed the nitrate drinking water standard. The communities were forced to install nitrate removal systems at costs of $600,000 and $2.1 million respectively. The recharge zones for the municipal wells contain irrigated agriculture (51% of the area for Whiting, 50% for Plover), forest (11% and 36%), dryland agriculture (7% and 5%), unsewered residential (11% and 2%), sewered urban (17% and 5%), and other (3% and 2%).

Mechenich and Kraft calculated the steady-state nitrate-N as

$$\text{Steady-state nitrate-N concentration} = \frac{\text{Mass of nitrate-N loaded to groundwater annually}}{\text{Volume of annual groundwater recharge}}$$

Groundwater recharge rates were assumed to be 8" per year on irrigated land and 10" per year on all other lands. An implicit assumption is that denitrification does not occur in the study area aquifer. The mass of nitrate-N entering groundwater can be calculated as:

Mass nitrate-N from row crops + Mass nitrate-N from legume forage +
Mass nitrate-N from manure + Mass nitrate-N from residences.

"Mass of nitrate-N from row crops" is equal to the average crop census (acres) times the nitrate-N loading rate (lbs. nitrate-N/acre) for each crop. Mechenich and Kraft used a three-year average crop census to estimate the acreage of each crop, and the N-budget approach of Stites and Kraft (1997) to estimate each crop's nitrate-N loading (Figure 3). In both recharge areas, irrigated potato, snap bean, and field corn were the main crops and covered roughly equal acreage. Smaller areas were devoted to dryland field corn and other irrigated and nonirrigated crops. The budget based nitrate-N loading rates were highest for conventional practice potato, sweet corn, and snap bean, amounting to 130-150 lbs/acre. The use of university recommended N fertilizer rates was only able to reduce loading by about 20-40 pound per acre for these crops.

Nitrate-N loaded from forages and manure were calculated somewhat differently, and probably underestimated loading, however, the final calculation of average basin nitrate-N concentration was likely only slighted affected. Nitrate-N loaded from residences was based on a 10 pound per person per year nitrate-N loading from septic systems and 8 lbs/acre for lawns. Additional details are in Mechenich and Kraft.

Results are summarized in Table 2. For conventional practices, predicted steady-state nitrate-N concentrations are 38 mg/L for the Whiting recharge area, and 26 mg/L for Plover. Full farmer adoption of university recommendations decreases the predictions to 26 mg/L for Whiting and 19 mg/L for Plover. These concentrations are about 1.5-2 times higher than present values. Agriculture is responsible for 90-99% of the nitrate loading. Even eliminating all other sources of nitrate only marginally will bring down nitrate concentrations.

GENERALIZING THE BASIN-SCALE NITRATE IMPACTS

The nitrate impacts of agriculture on WCSP groundwater basins, as demonstrated above, can be generalized. Table 3 represents one simplified approach to generalization, where the only needed data are the nitrate loading rate from agriculture and the density of the agricultural land use. Assume, for instance, that one wants to know what the average nitrate concentration would be in a groundwater basin where irrigated vegetable agriculture covers 50% of the basin surface,

Table 2. Some predictions of future nitrate concentrations in the Whiting and Plover municipal well zone of contribution, and an apportionment of sources.

	Whiting	Plover
Current nitrate-N concentration	20 mg/L	10-13 mg/L
Predicted future nitrate-N		
Conventional N rates	38 mg/L	26 mg/L
Universal university recommended rates	26	19
Where does the nitrate come from? % cover compared to % contribution	**% cover / % nitrate**	**%cover / % nitrate**
Irrigated ag	51 % / 65%	50% / 94%
Forest	11 / 0	36 / 0
Nonirrigated ag	7 / 27	5 / 5
Residential - unsewered	11 / 6	2 / 0.5
Residential and urban - sewered	17 / 2	5 / 0.5
Grassland	2 / 0	2 / 0
Other	11 / 0	1 / 0

Table 3. Nitrate-N concentrations in WCSP groundwater basins that result from combinations of agricultural loading rates (lbs nitrate-N/acre-year) and percentage of land in agriculture.

Agricultural area (%): are	**25%**	**50%**	**75%**	**100%**
Nitrate-N loading rate (lbs /acre-yr)	- - - - - - - - - mg/L nitrate-N - - - - - - - - -			
25	2	5	8	11
50	5	10	16	22
100	9	20	31	45
150	14	30	47	67
200	19	40	63	89

and uses a potato - sweet corn - snap bean rotation. If University fertilizer-N recommendations are used and average crop yields are attained, the average annual nitrate-N loading is about 100 lbs/year (Figure 3). This results in a predicted basin-averaged nitrate-N concentration of 20 mg/L. If 75% of the basin is covered by this land use, the nitrate-N averages 31 mg/L, and so on.

Table 3 could be used to determine what an acceptable loading rate might be to meet some groundwater goal. Assume, for instance, that a goal is to have basin-scale groundwater quality average less than 10 mg/L. Further assume that 50% of the land is in agriculture, and all other land uses contribute negligible amounts of nitrate. To attain the groundwater goal, nitrate-N loading needs to average less than 50 lbs/acre on agricultural lands.

Such a simplified approach may be useful in designing better agricultural practices for groundwater protection.

CONCLUSION

Nitrate concentrations continue to increase in WCSP groundwater basins. Most of the nitrate is from agriculture. Current approaches for minimizing nitrate loading - i.e., use of University recommended fertilization rates - are insufficient to meet groundwater standards. New approaches are needed for managing nitrate loading rates. Such approaches could target limiting nitrate loading through rotations, or through managing the density of agricultural practices in a groundwater basin.

LITERATURE CITED

Albertson, P.N. and B. Shaw. 1998. Little Plover River study. Pesticide research contract #95-03 to Wisconsin Department of Agriculture, Trade and Consumer Protection. University of Wisconsin - Stevens Point, WI

Central Wisconsin Groundwater Center. 1994. Conference Proceedings: Nitrate in Wisconsin's Groundwater: Strategies and Challenges, May 10, 1994, Central Wisconsin Groundwater Center (UWEX), Golden Sands RC&D, WI Dept of Natural Resources and WI Dept. of Health and Social Services.

Curwen, D., G. Kraft, T. Osborne, and B. Shaw. 1991. Demonstration of low input strategies for potato/vegetable production on irrigated sands. Final report for Wisconsin Department of Agriculture, Trade, and Consumer Protection Agricultural Demonstration Project #8810.

Hallberg, G.R. 1989. Nitrate in groundwater in the United States. IN: Nitrogen Management and Groundwater Protection. Elsevier, Amsterdam, pp. 35-74.

Hecnar, S.J., 1995. Acute and Chronic Toxicity of Ammonium Nitrate Fertilizer to Amphibians from Southern Ontario, Environmental Toxicology and Chemistry, vol. 14 no. 12, pgs 2131-2137.

Kincheloe, J.W., G.A. Wedemeyer, and D.L. Koch, 1979. Tolerance of Developing Salmonid Eggs and Fry to Nitrate Exposure, Bulletin of Environmental Contamination and Toxicology, vol. 3, pgs. 575-578.

Kraft, G.J. and W. Stites, 1999. Impacts of irrigated vegetable agriculture on a humid north-central U.S. sand plain aquifer. Ground Water 37:572-580.

LeMasters, G. and J. Baldock, 1997. A Survey of Atrazine in Wisconsin Groundwater, Final Report, WI Departement of Agriculture, Trade and Consumer Protection.

Mason, J.W., G.D. Wegner, G.I. Quinn and E.L. Lange. 1990. Nutrient Loss Via Groundwater Discharge from Small Watersheds in Southwestern And South Central Wisconsin, Journal of Soil and Water Conservation, vol.45, no.2 pgs. 327-331.

Mechenich, D.J. and G.J. Kraft. 1997. Contaminant source assessment and management using groundwater flow and contaminant models. Central Wisconsin Groundwater Center, University of Wisconsin - Stevens Point.

Shaw, Byron, 1994. Nitrogen Contamination sources: A Look at Relative Contributions, IN: Conference Proceedings: Nitrate in Wisconsin's Groundwater: Strategies and Challenges, May 10, 1994, Central Wisconsin Groundwater Center (UWEX), Golden Sands RC&D, WI Dept of Natural Resources and WI Dept. of Health and Social Services.

Stites, W. and G.J. Kraft. 1997. Agrichemical loading to groundwater under irrigated vegetables in the central sand plain. Central Wisconsin Groundwater Center. University of Wisconsin - Stevens Point.

Stites, W. and G.J. Kraft. 2000a. Groundwater quality beneath irrigated vegetable fields in a north-central US sand plain. Accepted to J. Env. Qual.

Stites, W. and G.J. Kraft. 2000b. Nitrate and chloride loading to groundwater beneath irrigated vegetable fields in a north-central US sand plain. Submitted to J. Env. Qual.

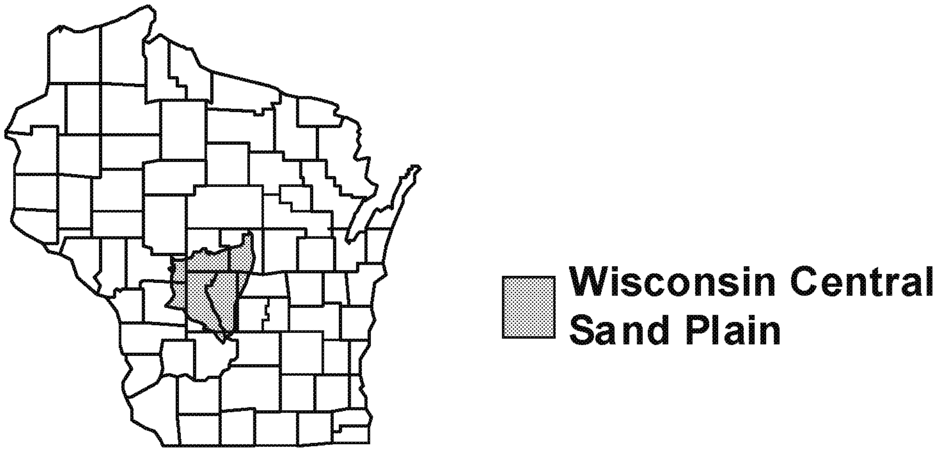

Figure 1. Location of Wisconsin Central Sand Plain (WCSP).

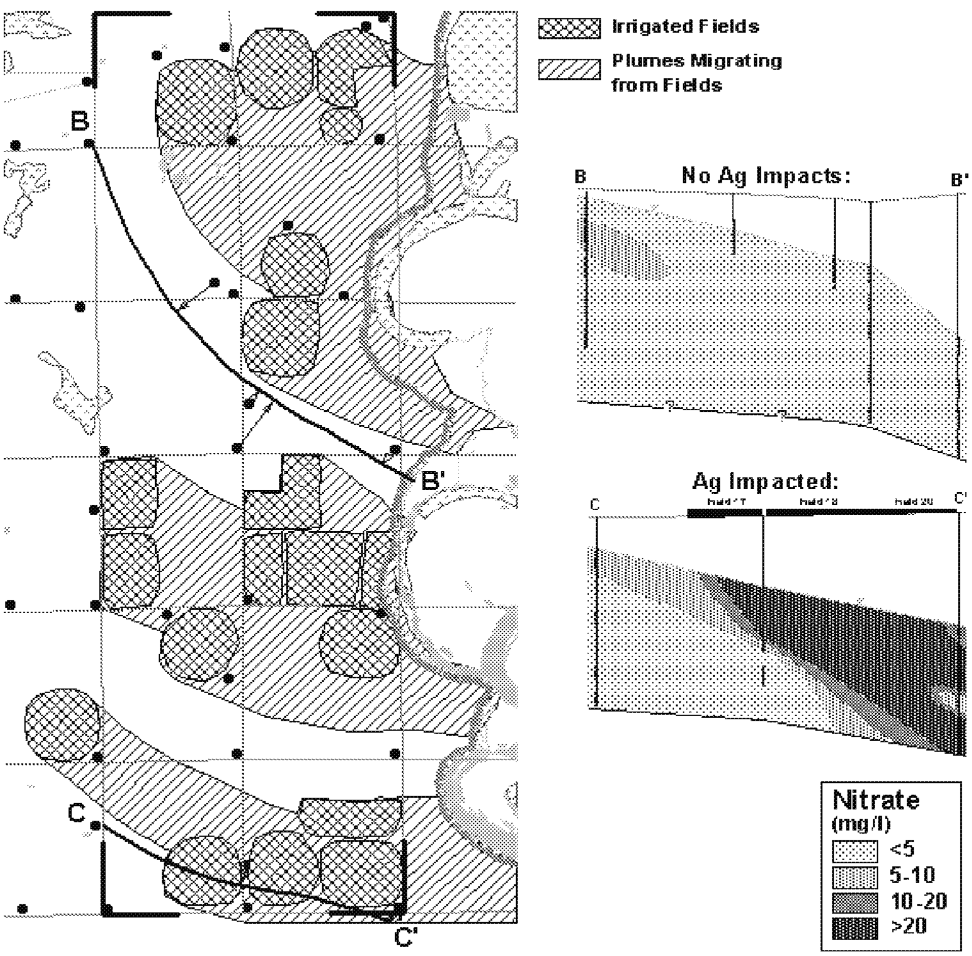

Figure 2. Plumes migrating from irrigated fields in the Port Edwards Groundwater Priority Watershed. Cross sections compare groundwater quality in agricultural plumes to background groundwater quality.

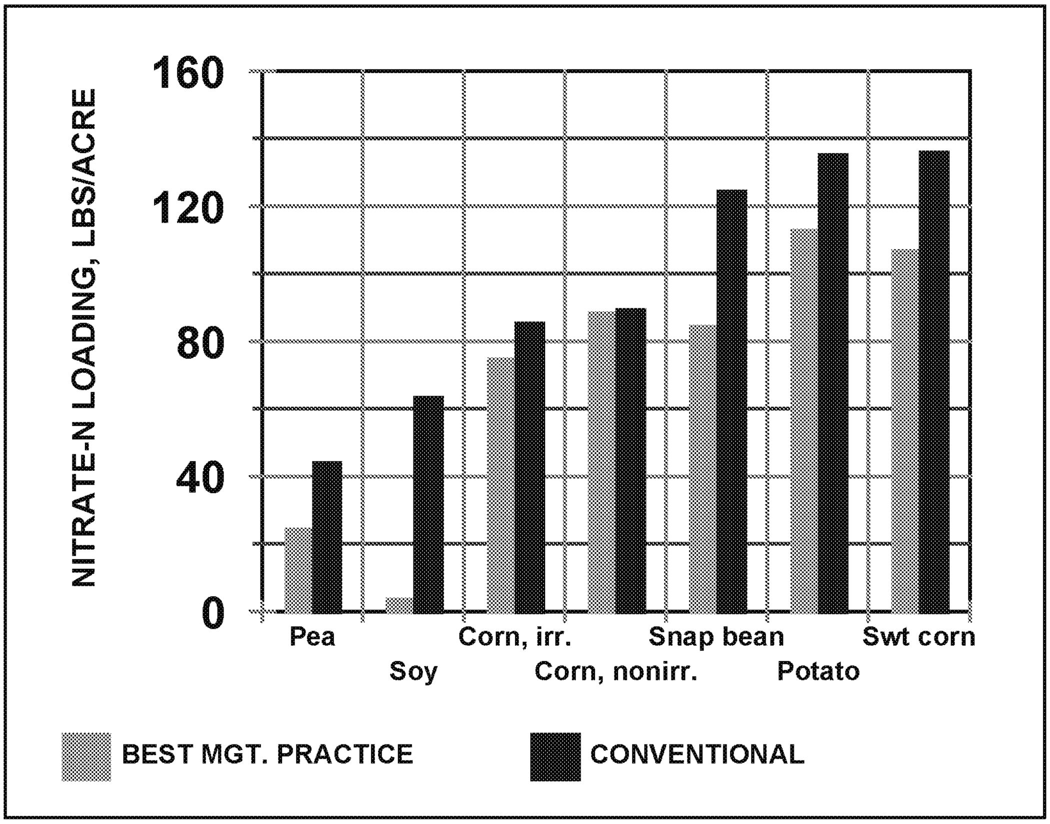

Figure 3. Budget-derived nitrate-N loading to groundwater under selected WCSP crops, for University recommended best management practices and conventional practices.

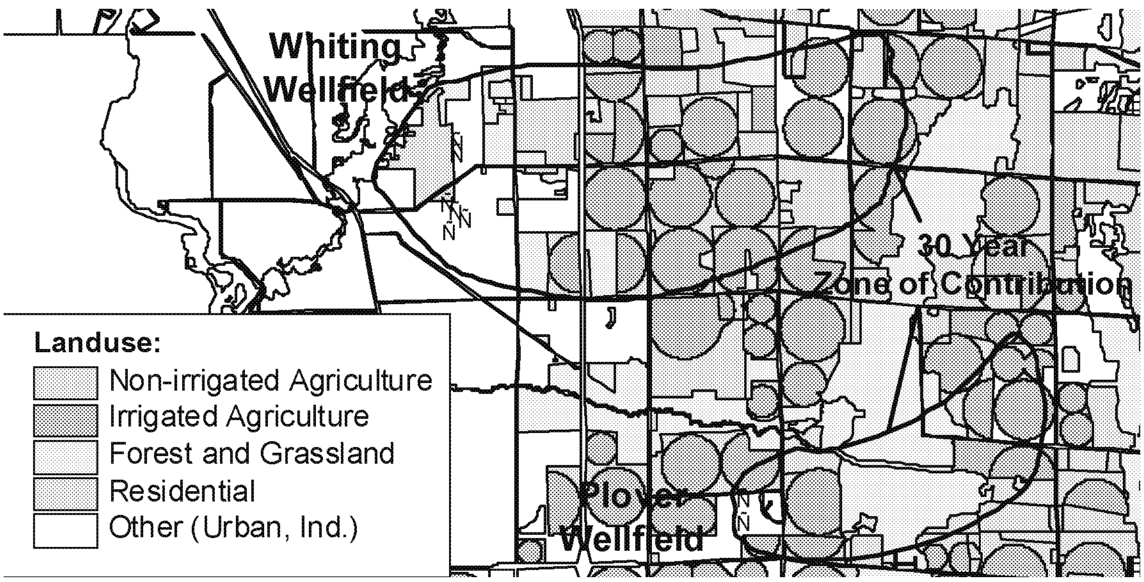

Figure 4. Land uses in the groundwater recharge areas for the Villages of Whiting and Plover municipal wells.